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Numerical Study of a Dielectrophoresis Separation Device at Multiple Frequencies

Baoyu Song[a], Deli Liu[b]*, Lining Sun[b], Liguo Chen[c]a

[a]Department of Mechanical Design, Harbin Institute of Technology, Harbin, 150001, China
[b]State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, 150080, China
[c]Robotics and Microsystems Center，Soochow University，Suzhou, 215021，China

Abstract

This paper presents a novel dielectrophoresis (DEP) chip for lateral separation of cells/particles at multiple frequencies. DEP force was enabled by interdigitated electrodes fabricated in the access channel. The non-uniform electric field distribution in the micro-channel is solved through finite element analysis. To improve the effectiveness of separation, the shape of insulators is optimized and other parameters such as the width of the electrodes are studied by introducing parameter K which can stand for the DEP force imposed on cells/particles. It is proved that planar electrodes can take place of 3D electrodes under certain condition. Furthermore functions realized by 3D electrodes can also be achieved by simple planar electrodes.

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Key words: Lab-On-Chip, Dielectrophoresis, Particle focusing

1. Introduction

Isolation and separation of interest cells/particles from a biological sample is one of the fundamental processes in many biomedical applications. The isolation of targeted cells from a complex tissue permits better characterization of a specific cell property, of drug effects and differentiation factors [1]. Dielectrophoresis (DEP) is one such method, exerting forces on particles via dipoles that are induced by electric field gradients. One attractive feature of DEP is that it allows particle manipulation without the

* Corresponding author. Tel.: +86-0512-67587217; fax: +86-0512-67587217.
E-mail address:drliudeli@gmail.com.

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need for tagging the particles. DEP-based manipulation has been successfully demonstrated for trapping [2, 3], separating [4, 5] and sorting [6, 7] cells and particles.

Continuous separation and focusing of cells in a microfluidic channel have been demonstrated by using of balanced lateral dielectrophoresis at multiple frequencies. The lateral dielectrophoretic forces are generated either by arrays of independent 3D interdigitated electrodes located in the sidewalls of a main channel[8] or by arrays of interdigitated planar electrodes in the access channel along the main channel that utilized ‘‘liquid electrodes’’. The main advantage of the sidewall electrodes is that it can provide a strong electric field covering the entire channel. But it is difficult to fabricate sidewall electrodes and the other effect caused by the variation of the electrical field is not considered. Furthermore, the DEP-force and its direction can be generated at particular and desired locations in the main channel by using ‘liquid electrodes’. However the throughput is a potential limitation since the height of the channel cannot extend beyond the reach of the electrical field generated from the planar electrodes.

In this study, a novel DEP chip is proposed and investigated through numerical simulation. The geometrical parameters of this scheme, such as shapes of insulators, width of electrodes and insulators are studied in order to achieve an ideal electric field distribution. Moreover, we discussed the similarity and replaceable condition between planar electrodes and sidewall electrodes.

2. Numerical Model and Governing Equations

The Laplace equation is used to solve the electric field, which can be expressed as:

$$\nabla^2 \mathbf{V} = 0 \tag{1}$$

$$\mathbf{E} = -\nabla \mathbf{V} \tag{2}$$

Figure 1 shows the 2D schematic of the chip, The DEP chip have a main channel and array of electrodes in dead-end channels (access channel) on each side. The width of the main channel, access channel and electrode are 50μm, the height of the channel and electrodes are 50μm. The interdigitated electrode array is fabricated on the top of a glass substrate using microfabrication techniques, and the channel is bonded with the substrate that forms the DEP chip. The medium solution flows in the channel from inlet to outlet. There are several pairs of electrodes but the electrodes are distributed periodically, so only two pairs of the electrodes is considered in the computation domain.

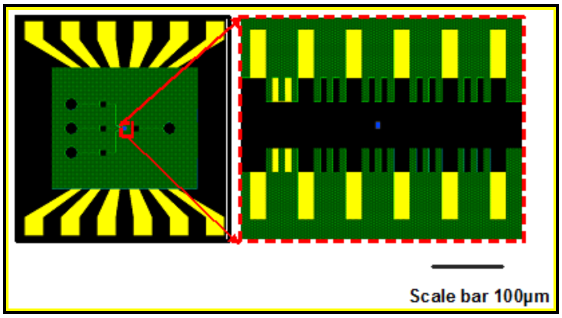


Fig. 1. 2D schematic of the chip

To achieve lateral separation, interdigitated electrodes on one side of the channel can be used to generate a DEP force along the width direction of the channel and a second DEP force is used to counter the first DEP force by electrodes on the opposite side. If the two sets of electrodes are applied the same

AC signal, the objects will be focused at the middle of the main channel. If a third AC signal is added to one side of the electrodes, mixed cell/particle populations are separated by the coupled DEP forces and then directed into different channel outlets. The equilibrium positions of different cell population satisfy the following formula [8].

$$\mathrm{Re}\left[K(\omega)_2\right]\nabla\mathbf{E}_2^2\Big|_y = \mathrm{Re}\left[K(\omega)_1\right]\nabla\mathbf{E}_1^2\Big|_y + \mathrm{Re}\left[K(\omega)_3\right]\nabla\mathbf{E}_3^2\Big|_y \qquad (3)$$

Due to the different dielectric properties of particles, dissimilar particles will be focused on different equilibrium planes across the width of the channel. When coupled with fluid flow, this result in lateral separation along the width of the channel.

Considering that $\partial\mathbf{E}^2/\partial y$ is the key factor for lateral separation and different insulator shape will generate different $\partial\mathbf{E}^2/\partial y$ distribution, semi-cycle and rectangular type insulators are analyzed. The shapes of the insulators are optimized in such a way that it can provide maximum $\partial\mathbf{E}^2/\partial y$ through the whole main channel.

Figure 2 shows the $\partial\mathbf{E}^2/\partial y$ distribution for two types of insulators. To achieve lateral separation, $\partial\mathbf{E}^2/\partial y$ distributions along the y axis at different x locations are important because greater $\int(\partial\mathbf{E}^2/\partial y)dy$ can provide greater $\mathbf{F}_{DEPy}$. As $\partial\mathbf{E}^2/\partial y$ distributions along the y axis is x location-dependent, it is necessary to find out $\partial\mathbf{E}^2/\partial y$ distributions where $\int(\partial\mathbf{E}^2/\partial y)dy$ is maximum and minimum for different insulator shapes.

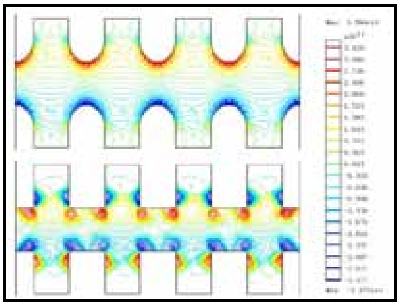


Fig. 2. Top view of the electric field strength distributions for two types of insulators: (top) semi-circle type insulators, (bottom) rectangular type insulators.

The $\partial\mathbf{E}^2/\partial y$ variation curves for the two insulators shapes at where $\int(\partial\mathbf{E}^2/\partial y)dy$ is the minimum are show in Figure 3.

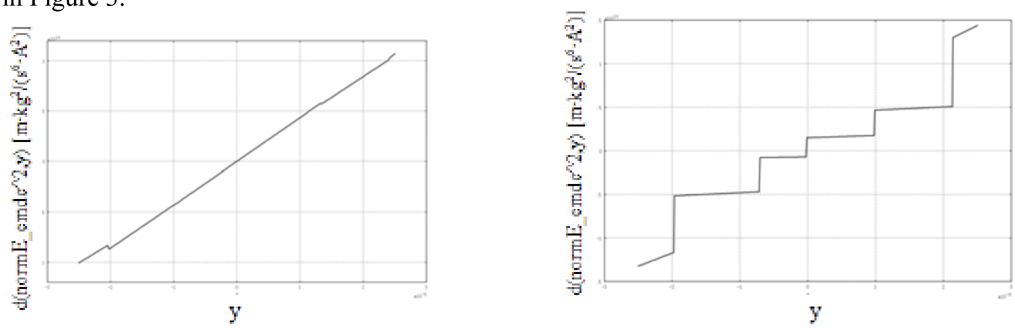


Fig. 3. The $\partial\mathbf{E}^2/\partial y$ variation curves for the four insulators shapes at where $\int(\partial\mathbf{E}^2/\partial y)dy$ is the minimum: (left part) semi-cycle type insulators, (right part) rectangular type insulators.

To compares the remaining types, the curve for each project is changed to a line whose slope is K and goes through origin. A parameter K is defined as follows to estimate the $\mathbf{F}_{DEPy}$ value:

$$K = \frac{4\times\sum_{i=1}^{n}|y_i|}{n\times b} \tag{4}$$

where y_i is the y value of the curve in each figure, n is the total number of the sample points in the horizontal direction, b is the width of the main channel which is defined as 50μm in this model.

Then $\mathbf{F}_{DEPy}$ can be written as follow:

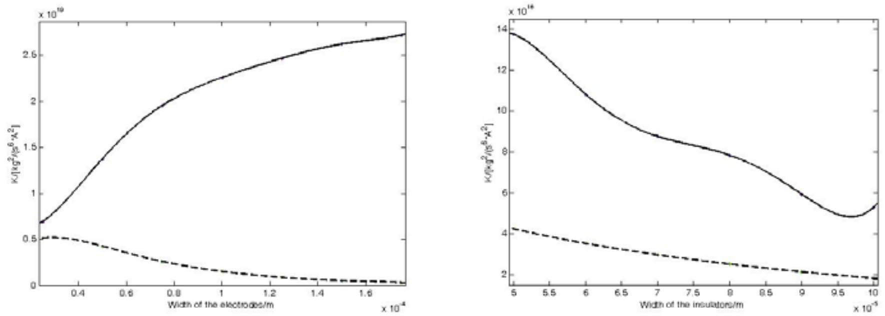
$$\mathbf{F}_{DEP\,y} = 2\pi r^3 \varepsilon_m^* \operatorname{Re}\left[K(\omega)\right] * K * y \tag{5}$$

Table 1 lists the K where $\int(\partial \mathbf{E}^2/\partial y)dy$ is maximum and minimum for each type from where it can be concluded that semi-cycle type insulator can generate the greatest $\partial \mathbf{E}^2/\partial y$ in the main channel. ($K_{\max}$ is defined as the K at where $\int(\partial \mathbf{E}^2/\partial y)dy$ is maximum and $K_{\min}$ is defined as the K at where $\int(\partial \mathbf{E}^2/\partial y)dy$ is minimum)

Table.1. $K_{\max}$ and $K_{\min}$ for different type of insulators

type	A	B
$K_{\max}$[kg^2/(s^6*A^2)]	1.3749×10^{19}	4.2443×10^{18}
$K_{\min}$[kg^2/(s^6*A^2)]	4.2443×10^{18}	2.9667×10^{18}

Figure 4 shows K variations with the width of the electrodes and the insulators. $K_{\max}$ increases with the width of the electrodes, but $K_{\min}$ decreases. When the width of the electrodes is longer than 120μm, $K_{\max}$ is two orders of magnitude bigger than $K_{\min}$. As $K_{\min}$ locates in the middle line of the electrodes, wider electrodes will generate less $\mathbf{F}_{DEPy}$ in the main channel. So the width of the electrodes should not be too long. $K_{\max}$ and $K_{\min}$ both decrease with the width of the insulators and $K_{\max}$ decreases faster than $K_{\min}$, therefore, the width of the insulators also should not be too long.



A B

Fig. 4. K variation curve: (left) with the width of the electrodes; (right) with the width of the insulators.

The possibility of using planar electrodes to replace 3-D electrodes should be discussed because of the complexity of fabrication for 3D electrodes. Only if the $\partial \mathbf{E}^2/\partial y$ distribution generated by planar electrodes is similar to the one generated by 3-D electrodes, the two kinds of electrodes can realize the same function. For planar electrodes, there will always be dead electrical field space farther away from the bottom of the channel. $\partial \mathbf{E}^2/\partial y$ decays along the height of the channel and this will decrease the efficacy for DEP manipulation. If the attenuation degree is not too great (two or more orders of magnitude), it can be used to make up for the attenuation by adding the number of the electrodes which is quite simple for planar fabrication. Planar electrodes can replace 3D electrodes which may not influence the efficacy of DEP manipulation by using more pairs of electrodes.

3. Conclusions

This paper proposes a DEP chip for lateral separation. Moreover the separation principle was introduced. The insulator shape is optimized by numerical analysis in the way that introduces a parameter K which stands for the DEP separation force during the cell/particles motion and semi-circle type insulator is proved to be the most suitable for it can provide the strongest DEP force used for separation. It is found that planar electrode can take place of 3D electrode by adding the number of electrodes without decreasing the efficacy for DEP manipulation under the condition that the height of the channel is within 50μm.

Acknowledgements

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